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Geology and Mineralization of the proximal Worthington offset area in the Sudbury Igneous Complex, Canada

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Theses of PhD Dissertation

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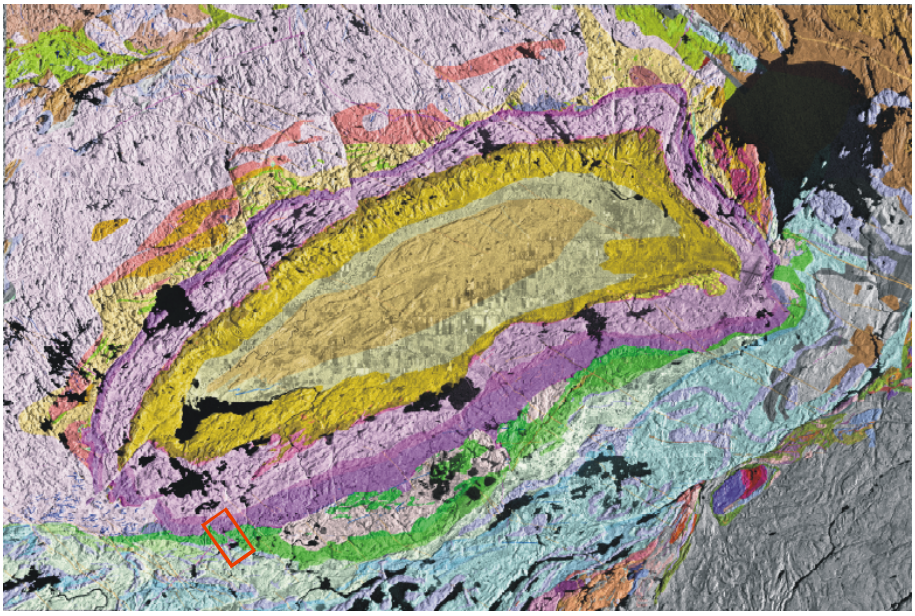

The Sudbury Igneous Complex (SIC), Ontario, Canada; b&w landsat image overlain by geology of the SIC, red rectangle indicates the area of research presented in this study

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SUMMARY AND CONCLUSION OF STUDY

.1. Geological Mapping

Detailed geological outcrop field mapping of an approximately 4 km^2 area has been competed between 2000 and 2003 at the proximal Worthington quartz diorite offset area in the South Range of the Sudbury Igneous Complex. Mapping has started from the northwest toward the southeast the Vermilion mine in order to complete a section across the SIC contact and follow the general northwest-southeast trend of the quartz diorite occurrences. At the peripheries of the area geological information has been complied using INCO exploration map sheets (L-50-W and K-50_W) and interpretation of aerial photographs. The map presented in this Thesis is a geological interpretation map based on outcrops.

The final geological map indicates that quartz diorite of the proximal Worthington offset occurs in several irregular-shaped sheets, segmented tectonically by east and northeast trending fault and shear zones. They intrude metavolcanic and minor quartz-rich metasedimentary rocks of the Elsie Mountain Formation north of the Creighton fault. South of the Creighton fault a funnel-shaped quartz diorite intrudes the Matinenda Formation metasediments, comprising interlayered quartzite, wacke and feldsparic wacke. The Matinenda Formation rocks are intercalated with massive amphibolites of the Stobie Formation following general northwest-trending lithological boundaries. The funnel-shaped quartz diorite follows this trend as well, defined by northwest-trending lithological sequences within the Matinenda and Stobie Formations. The quartz diorite however plunges underground ad can be followed for another 400 metes. The Vermilion quartz diorite occurs 900 meters to the east from this location. Quartz diorite at the Vermilion mine appears in three separate bodies intruded in a composite Sudbury Breccia dominated by a biotite-rich foliated matrix and a subordinate amphibole-rich matrix.

To the north of the Creighton Fault quartz diorite occurs in two major bodies and two small faulted fragments. The large quartz diorite body to the immediate north of the fault has a shape like a bent funnel, probable resulting from superposition by parallel set of faults and shear zones. Close to margin of the intrusion, within a 3 to 7 meter zone a finer-grained “chilled” margin develops and it has gradual “ill defined” transition to the coarser-grained central facies. Outcrops around the Victoria mine indicate strongly brecciated country rocks along quartz diorite intrusion. Limited outcrops to the north of the caped Victoria mine shaft suggest that quartz diorite may have formed a funnel-shaped embayment at the base of the SIC. Detailed mapping indicated that there is no transition between the SIC rocks and the Victoria quartz diorite but a very sharp tectonic contact; the Victoria Shear Zone. To the north

of the shear zones quartz-rich basal norite, very similar to quartz diorite, occupied the lowermost zone of the SIC. Between quartz-rich basal norite and the Footwall amphibolite, xenolithic mineralized Contact Sublayer may be a 10 to 30 meter wide 800 meter long intrusive unit. The intrusive relationship is difficult to ascertain due to the presence of numerous narrow northeast-trending shear zones subparallel with the main Victoria Shear. As a consequence apparent intrusive relationship may be the result of stacking and repetition of footwall and Contact Sublayer blocks along the numerous shear zones. The 800 mete long Contact Sublayer is segmented into several pieces by these shear zones and dislocation is up to 30 meters between faulted fragments. Most of the best mineralized surface outcrops consist of massive lenses of remobilized sulphides along the shear zones. The deformation zones are present to the north of the Victoria mine, they occur 30 to 70 meter apart and became more frequent to the north where they merge into a coherent zone of shearing, the South Range Shear Zone.

2. Mineral occurrences

Surface outcrop mapping of the proximal Worthington offset area located and outlined several sulphide-PGE occurrences which were evaluated by reconnaissance assay sampling. A later exploration program by FNX Mining Inc. in 2002-2003 named these occurrences as Far West, No2. West, No.1 West, Central, No.4 and Powerline -zones. Significant Cu Ni grades (0.24-2.70 % Cu and 0.2-3.54 % Ni) with slightly elevated PGE (0.138 ppm Au+Pd+Pt) were found only in massive sulphide lenses and streaks of re-mobilized sulphide ore along the shear zones north of Victoria mine. On surface the mineralization of the No.2 West Zone in confined within a 300 meter long 5 to 30 meter wide northwest-trending Sublayer body crosscut by several shear zones. Exploration drilling by FNX in 2002-2003 identified this zone to the most significant mineral occurrence of the proximal Worthington offset area.

The blebby- and disseminated –sulphide mineralization at several places in the quartz diorite bodies to the south of Victoria Shear Zone did not yield promising assay results (max. 0.63 % Cu and 0.65 % Ni) and have limited surface dimensions. Significant PGE-enrichment (0.8-4.14 % Cu with 1.1-4.83 ppm total PM (Pt+Pd+Au) however was found in a small mineralized biotite-rich Sudbury Breccia occurrence. This zone is the only surface outcrop of the Powerline Deposit that was discovered by exploration drilling during 2002-2003 by FNX.

The area south of the Creighton Fault is mostly covered by introspective metasediments. The most significant Ni-Cu-PGE mineralization of this area is the Vermilion quartz diorite. Grab assay samples from several outcrops of mineralized quartz diorite at the

abandoned mine site yielded extreme high values (77-134 g/t total PM; Pt+Pd+Au) not very common for PGE occurrences of the SIC.

3. Structural Analysis

Detailed field mapping, macroscopic and micro-structural analysis of deformation zones of the northern block of the map area indicate that the northeast-trending parallel protomylonite and mylonite zones have formed by thrust faulting of SIC and footwall amphibolites of the Elsie Mountain Formation. The tectonics in these deformation zones appears to be L-S tectonics in which foliation is defined by mica rich layers and lineation is marked by the stretching lineation of micas and striation. All the mapped shear zones strike to the NE-E (60-90) and dip to S-SE (150-180) with angles varying slightly between 60 and 90 degrees. Microtextural characteristics correspond to two textural types of deformation; protomylonite and mylonite. In brittle shear zones protomylonite contains 50-60 % 0.1 to 2 mm sub-angular to well-rounded porphyroclasts of plagioclase in 40-50 % chlorite-rich foliated matrix. The host rock blocks between the slightly anastomosing and branching shear zones do not exhibit pervasive foliation but are strongly altered to chlorite carbonate. In mylonites, host rocks partially or completely re-crystallized to biotite, biotite-chlorite and chlorite schist. The schistose mylonite zones are associated with the Victoria Shear Zones within a 200 meter distance whereas protomylonite usually develops in shear zones located to the north hosted by South Range Norite. Systematic thinsection samples were collected from a number of both types of deformation to analyze kinematic indicators in order to deduce the sense of shear. In protomylonite the tiling of broken plagioclase grains were statistically analyzed.

In mylonite zones the host rocks are re-crystallized into chlorite-rich cleavage band and quartz-carbonate microlithons. In some samples quartz grains have developed shape-preferred orientation (SPO) but in all they show weak to moderate lattice-preferred orientation LPO indicative of general (noncoaxial shear) and thrusting; south side to the northwest. These L-S tectonites developed within the deformation zones have the same bulk vorticity and orientation that of the South Range Shear Zone 3 kilometres to the North. Therefore theses deformation zones are identical with the South Range Shear Zones and may represent the southernmost splays or subsets of it. Based on the close similarity of structural elements observed and studied from shear zones in the mapping area and the close proximity of the SRSZ, the timing of deformation must be equivalent to the South Range Shear Zones.

4. Geochronology Studies

The deformation zones have macro-textural, microtextural and kinematic characteristics identical not only to the SRSZ but to the deformation zone of the Chief Lake intrusive complex, at the Killarney area, dated 1450 Ma: This northeast-trending zone runs parallel with the Grenville Front, and located about 40 km to east of the mapping area. Given this possibility to see the same age of deformation of the mapping area, potassium-bearing syn-kinematic minerals were located and systematically collected for radiometric K/Ar and Ar/Ar geochronology studies. In the major shear zones all biotite is altered to chlorite, therefore biotite was sampled from minor 30 cm to 1 m wide shear zones in Nipissing Gabbro north of the Victoria mine and muscovite, mariposite (Cr-muscovite) were sampled from the Victoria Shear zone and a subparallel zone. In addition biotite was separated from the amphibole-biotite quartz diorite of the Victoria embayment. One coarse contact metasomatic brown amphibole (Ti-hornblende) was sampled from a quartz-albite-amphibole nest. One biotite sample was collected from the deformed granophyre in the SRSZ, 15 km to northeast of the map area K/Ar radiometric ages were established for the eight samples al span between 1330 Ma and 2000 Ma. All shear zone samples span around 1410-1490 Ma +/- max. 60 Ma such as the biotite in altered quartz diorite 1463-1481 Ma +/-56 Ma. The younger age of deformed granophyre in the SRSZ is attributed the very fine biotite fraction of that sample. The oldest age 2000 +/- 77Ma was obtained for the contact-metasomatic Ti-hornblende. The age of deformation appeared to be established at around the expected age 1450 Ma the Chieflakian contractional deformation period of the Mesproterozoic Era.

To confirm the K/Ar results Ar/Ar geochronology studies were repeated on five samples. Measurements were performed at Simon Fraser University, Canada. All samples yielded interpretable plateau ages 1377-1482 Ma +/- max. 7.8 Ma comparable with the K/Ar studies. For the Ar/Ar studies one coarse (1cm) porphyroblastic amphibole from the thermal contactmetamorphic aura of the SIC was sampled and yielded 1716.5±9.2 Ma coinciding with a regional organic event the Mazatlzal-Labradorian age, 1.7-1.6 Ga. Based on field mapping and petrographic observation the age is considered to be reacted to protracted cooling of the SIC with superimposed regional metamorphic event, indicated by Ti-free hornblende rims on all porphyroblasts.

Based on the K/Ar and Ar/Ar studies of deformation zones at the Victoria mine area it is proposed that the bulk deformation of the SIC along the SRSZ may be rated to the 1450 Ma. Chieflakian contractional orogenic event.

5. No.2 West Zone sulphide-PGE mineralization

In conclusion this study showed that, in the No.2 West Zone mineralization, local northeast-trending shear zones associated with the 1450 Ma Chieflakian deformation of the Sudbury Structure could have played major role in re-distribution and re-mobilization of primary magmatic sulphides and PGE-minerals. Deformation within primary magmatic sulphide mineralization could have caused transformation of ore-texture, change of bulk mineral composition and local enrichment of PGE minerals. Association of PGE-minerals with hydrous silicate minerals carbonates and abundant complex highly saline H_2O-NaCl-$CaCl_2$-CO_2-CH_4-N_2 inclusions in quartz and carbonate indicate that PGMs could have precipitated by this fluid at temperature of 400-550°C and pressure of 2-2.6 kbar. This fluid preferentially circulated along the deformation zones and could be originated by mixture of highly saline shield brines and CO_2 –rich metamorphic fluids concentrated along the shear zones. The highly saline fluids and CO_2 –rich fluids have limited miscibility field therefore it is suggested, based on petrography, that at 400-550 °C temperature they have trapped heterogeneously from an immiscible system.

These results demonstrate that deformation of primary magmatic sulphide ores accompanied by metamorphic-hydrothermal alteration could result in the local PGE enrichment in zones within the magmatic sulphide environment.

6. Vermilion Mine Sulphide-PGE mineralization

The 1.85 Ga impact-related brecciation in the 2.4 Ga Huronian metasedimentary-metavolcanic footwall rocks led to the development of SDBX (powdery rock flour, frictional melts and host rock fragments) preferentially along lithological contacts of different competency where strain was released effectively. Rigid intrusive bodies of the 2.4 Ga Nipissing gabbro were fractured into larger blocks by the flowing SB that may have grouped lower density smaller feldspathic and amphibolitic inclusions into the high velocity central areas of the flow, but could not completely organize the gabbro blocks. One or more intrusions of partly crystallized magma occurred in the consolidated and colder SB that carried magmatic sulphide blebs. Parts of SB were heated by QD to 800-1000°C/1.5-3 kbar to form high-Ti pyroxene- or hornblende-hornfels in very close proximity. The occurrence of granophyric texture may relate to fluid exsolution from Vermilion QD pods that could interact with magmatic sulphide blebs and re-mobilize Cu-Ni-PGE.

The first phase of hydrothermal mineralization produced an assemblage of maucherite (with sudburyite and gold inclusions)-nickeline-sperrylite followed by sulfarsenide,

michenerite, pentlandite and pyrrhotite crystallization with alteration minerals (biotite, garnet, epidote, quartz, zircon, rutile). This resulted in massive to semimassive ore shoots (that have been mined out) surrounded by a disseminated halo of sulphides and quartz sulphide veins. Highly saline (40-45 $NaCl+CaCl_2$ equiv. wt% fluids) at 350-510 °C and 2-4 kbar were responsible for depositing this assemblage. However, later hypogene alteration occurred that caused peculiar replacement textures; millerite-violarite replacing pentlandite, cobaltite-gersdorffite replacing both nickeline and maucherite, pyrite-marcasite replacing pyrrhotite, bornite replacing chalcopyrite and albite replacing epidote. This alteration may relate to the introduction of a late fluid, now represented by abundant secondary fluid inclusions in earlier veins and with the occurrence of finely-disseminated sulphide-PGM zones of different mineral assemblage and texture.

The assemblage of chalcopyrite-bornite-millerite-sulfarsenide and complex PGM (michenerite-froodite-hessite-sudburyite) with wittichenite-parkerite-gold-molybdenite postdate maucherite-nickeline. Exsolution textures in bornite containing PGM suggest that a precious-metal-bearing bornite solid solution cooled then broke down resulting in numerous exsolution forms containing PGM. Textural evidence also suggests that partial re-crystallization and hydrothermal alteration caused re-equilibration within this complex assemblage manifested by reaction rims, replacement relationships and the latest assemblage of annivite-luzonite-tennantite. Associated hydrous minerals chlorite, epidote and albite, carbonate and quartz are equivalent to a greenschist facies hydrothermal alteration. Chlorite with significant complex PGM assemblages replacing garnet-biotite SDBX syn-tectonically, suggests a genetic link of this assemblage to the non-pervasive brittle-ductile deformation. This deformation also caused alteration, straining and fracturing of sulphide-quartz veins of the earlier higher-T phase. Chlorite thermometry, fluid inclusion thermobarometry, mineral textures and paragenesis suggest conditions of 250-370 °C, 1-3 kbars for the formation of this assemblage.

Metamorphic processes in QD and SDBX indicate a maximum of upper greenschist-lower amphibolite facies garnet-biotite-amphibole assemblages of 370-510 °C, less than 5 kbar, conditions that may be coeval with the early higher-T hydrothermal mineralization phase. Greenschist facies alteration of this assemblage to chlorite-epidote-albite-(muscovite)-carbonate is associated with complex sulphide-PGM assemblages of the second phase. Deformation-related late carbonate enrichment in earlier quartz veins occurred at 100-200 °C. Hydrothermal fluids at these conditions could mobilize some Au-Bi-S. Low temperature

chlorite (pennine) may be associated with this latest phase with subgeenschist facies alteration in veinlets of the footwall.

The observed hydrothermal PGM assemblages (Table 10.3), and fluid composition temperature-pressure range are equivalent to those studied from Ni-Cu-PGM deposits in the eastern South Range and also recognized all around the Sudbury Structure. These hydrothermal processes have a very important role in redistribution of both Cu-Ni and PGE and the generation of high-grade Cu-Ni-PGE sulphide and high-grade PGE low sulphide deposits.

7. Crean Hill mine 4040 Level sulphide-PGE mineralization

A number of PGE and PM minerals have been identified and described from the 4040 level of the Crean Hill mine. The PGE-minerals are found in deformed magmatic inclusion-massive sulphides, minor sulphide and granophyric sulphide veins the massive amphibolite footwall. PGE-sulfarsenides are ubiquitous in the massive ore and often cored with irarsite or hollingworthite. Michenerite the most abundant Pd-mineral occur in massive ore associated with fractures and alteration minerals of biotite, magnetite, quartz, K-feldspar, garnet. Michenerite is associated with a large number of PMs and CO_2 –rich fluid inclusions in the granophyre-sulphide vein of the footwall amphibolite. The abundance of deformation features, equilibrium and disequilibrium textures of sulphide and metamorphic hydrous alteration minerals may suggest a magmatic hydrothermal to metamorphic hydrothermal overprint on the primary massive magmatic ore. Temperature, pressure constraints of this process may be comparable with the hydrothermal alteration observed in the Vermilion mine ie. 350-500 °C 2-4.2 kbar.

8. Sulphide and PGE-minerals identified from the proximal Worthington offset area and their genetical importance.

A large number of PGE minerals have been identified in three Ni-Cu sulphide deposits of the Proximal Worthington Offset area (Table 12.1). This data has significantly contributed to the knowledge of PGE mineralogy of deposits in the South Range where mineralogy data are limited compared to the North and east Ranges. The detailed genetical studies in the No.2 West and Vermilion deposits have not only identified these PGE minerals but also explained their mode of occurrence, paragenesis and proposed a magmatic hydrothermal to metamorphic hydrothermal origin for their relative enrichment in comparison with magmatic sulphide ores.

9. Significance of Fluid inclusion studies

There has been considerable debate about the role played by chloride-bearing hydrothermal fluids in concentrating or redistributing the PGE and Au in mafic igneous systems. In many mineralized systems host rocks exhibiting the greatest alteration intensity appear commonly to be positively correlated with PGE content. The solubility of Pt, Pd, Os, and Au in sulphide-bearing solutions, in low salinity chloride- and mixed sulphide-chloride-bearing fluids has been studied up to 500°C using a variety of classical hydrothermal experimental methods and conclusions indicate that although significant (greater than 10 ppb) hydrothermal Au transport by chloride is possible over a wide range of geologically-realistic conditions, the PGE are significantly soluble as chloride complexes at temperatures less than 500°C only under highly oxidizing, acidic, and saline conditions.

More recently it was demonstrated that single-phase hypersaline fluids (at condition 1.5 kbar and temperatures of 600 to 800 °C) which exsolve from or interact with residual magmatic liquids, partially crystallized rocks, or small volumes of PGE (platinum-group element)-Au-bearing sulphide can potentially dissolve and transport economically-significant amounts of Pt and Au across the magmatic-hydrothermal transition at moderately oxidizing conditions.

Fluid inclusion studies from hydrothermal Cu-Ni-PGE footwall mineralization around the Sudbury Igneous Complex have proven that highly saline high temperature hydrothermal fluids were responsible for the re-mobilization of PGE content of the primary Contact-type massive Ni-Cu-PGE sulphide ores and deposited the PGE minerals in veins and zones of disseminations. Most of these studies are reported from the North and East Ranges of the Sudbury Structure whereas considerable lesser studies have been reported from the South Range due to the more complex geological history of the highly deformed Huronian footwall rocks that hamper easy recognition of PGE-rich zones.

In this study new fluid inclusion and mineralogy data are provided for the South Range of the SIC and they support the recently widely accepted hydrothermal origin of footwall PGE mineralization. Moreover the finding of hydrothermal mineralizations in the south-western corner of the SIC illustrates that magmatic-hydrothermal systems have developed all around the periphery of the SIC, and the South Range could have similar exploration potential for Cu-Ni-PGE low sulphide type deposits to the North and East Ranges.

10. Publications

Molnár, F., Szentpéteri, K., (2005): Microscopic study of opaque minerals 185pp. (in Hungarian)

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Zajzon, N. & Szentpéteri, K., (2002): Plumbogummite from Szűzvár Mine, Pátka, Velence Mountains, Hungary: a new mineral species for Hungary, Acta Mineralogica Petrographica, Szeged, vol. 43, no.1, p. 5-20.

Szentpéteri, K. & Molnár, F., (2000): Mineralogical and genetical study of an adularia-sericite type epithermal deposit at the Szarvas Hill, Sárszentmiklós. (Adulár-szericit típusú hidrotermás indikáció ásványtani és genetikai vizsgálata a sárszentmiklósi Szarvas-hegyen) Földtani Közlöny, 130/1, p. 1-23 (in Hungarian with English abstract)